EXPLORATORY STUDIES: EFFECT OF ION IMPLANTATION ON THE FRICTION AND WEAR CHARACTERISTICS OF CUTTING TOOL SURFACES

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I. Introduction

Exploratory experimental studies have been undertaken to assess the effect of ion implantation on the friction and wear characteristics of cutting tool inserts and cutting tools. Two tool materials (M-2 High Speed Steel and TiC-coated Carbide) and a specific tool (1/4" x 20 taps) were tested. Implanted tools (carbon, boron, nitrogen and titanium) were tested in machining. Unimplanted tools were also tested to provide a basis for comparison. The test results obtained are presented, summarized and interpreted in this report.

II.a. High Speed Steel (M-2) Tests

Two series of tests were undertaken to evaluate the possible benefits of titanium ion implantation of M-2 high speed steel. The first series of tests were cutting force measurement studies to assess the effect of ion implantation on the tool-chip interface friction and on the specific power consumption during machining. The second series of studies were concerned with the effect of ion implantation on tool wear.

Fully hardened unimplanted and ion implanted M-2 high speed steel inserts were used in these studies. Unimplanted cutting tool edges were compared with those implanted with titanium ions (150 keV ions; 5×10^{17} ions/cm^2 fluence; ions implanted at the Naval Research Laboratory, Washington, D.C. by J. Hirvonen).

An annealed medium carbon steel (AISI 1045) was machined in a 7.5 kW (10 hp) lathe equipped with a continuously variable speed drive. The lathe is instrumented with a Kistler 3-component dynamometer, charge amplifiers, recorders and digital speed indicators. In all tests, the cutting tool inserts were held in a standard square insert tool holder which yielded a 6° positive rake during machining. To simulate semi-orthogonal cutting, an approach angle of 5° was used in the force measurement tests. In tool wear tests (flank wear tests), the normal 15° approach angle was used. Figure 1 illustrates the tool geometry during machining.

II.b. Test Results

As communicated to J. Hirvonen in a preliminary summary of findings (December 24, 1980) no consistent or discernable trends can be detected in the tool-chip interface friction with ion implantation. Specific power during machining is however found to be lower consistently. The data (triple replication on the same bar) obtained is presented in Table I.

Flank wear tests were carried out on the same log of steel. The tests were carried out at a cutting speed of 33.5 m/min., with a depth of cut of 1.5 mm and a feed rate of 0.125 mm/revolution. The speed and feed were chosen to obtain a flank wear of the order of 0.2 mm in about 20 minutes of cutting tests (actual cutting time). The results obtained are shown in Figure 2. While the unimplanted tool yielded a flank wear of approximately 0.25 mm in 10 minutes of cutting, the implanted tools did not produce a wear land of 0.20 mm in 20 minutes of cutting. The tests were run dry.

Tool wear tests under controlled laboratory conditions unambiguously show that titanium ion implantation leads to a lowering of flank wear rate in M-2 high speed steel tools.

III.a. Titanium Carbide Coated Tool Inserts

Chemical Vapor Deposition (CVD) coated WC-Co inserts were ion implanted and used to evaluate the effect of ion implantation on the friction and wear characteristics in machining. Carboloy Grade 515 or 516 inserts (both TiC-coated; they differ in substrate composition and mechanical properties. Since coating thickness, 5 to 10 μm, is much larger than the range of implanted species, substrate variation is not relevant) were implanted with carbon, boron or nitrogen.

In the case of M-2 high speed steel, titanium was implanted to take advantage of possible formation of TiC in the tempered matrix. In the case of the carbide, the expectation is to (a) form carbo-nitrides or (b) to form titanium diboride precipitates in TiC layers. Solution hardening and dispersion hardening are aimed for.

From previous work it is known that carbo-nitrides are much harder that carbides or nitrides. Carbo-nitride generation by ion implantation 'should work'. Boride precipitation requires elevated temperature treatment to assist boride formation. Hence "diffusion-treated" inserts are expected to perform better ($T \simeq 1000°C$; 2 hours in inert atmosphere).

Implanting carbon into a stoichiometric or near stoichiometric TiC should degrade its stoichiometry. Poorer performance should ensue.

Wear tests in particular can document this.

As in the case of H.S.S. inserts, cutting force tests and wear tests were carried out. Unimplanted tool edges were used to establish a base line. Negative rake tools were used (-6° double negative rake; side rake and back rake). Semi-orthogonal cutting tests (15° approach angle) were used. An annealed medium carbon steel (AISI 1045) was machined.

III.b. Test Results - Semi-orthogonal Cutting (As Implanted Tools)

Results obtained by machining the 1045 steel in the instrumented lathe are tabulated in Tables II to IV. The three components of the cutting forces measured, Figure 3, were used to calculate the operative tool-chip "friction". Power component of the cutting force F_c was used to determine changes in specific power consumption. Computed effective friction coefficients and specific power consumption for metal removal are furnished in Tables II and III. All of the test data reported were obtained from the same test bar.

At the upper end of the useful cutting speed range for the TiC-coated carbide inserts (approximately 200 meters per minute) boron, carbon and nitrogen implantation tends to lower the effective friction coefficient in that order. Apparently, implantation also tends to lower the specific power consumption for metal removal. Consistently lower specific power consumption is observed in carbon implanted TiC-coated cutting tool inserts. This is unexpected. Boron and nitrogen show no special trends.

III.c. Wear Test Data - As Implanted Tools

Long turning tests were carried out to evaluate the wear characteristics of unimplanted and implanted, TiC-coated carbide inserts. Calibration tests at 750 ft/min and 500 ft/min with unimplanted carbides indicated that in some 20 minutes of cutting, flank wear of 100 - 150 μm is obtainable. Based on this empirical observation, the following test conditions were chosen and used.

Material:	Annealed 1045 steel
Tool:	TiC-coated carbide (unimplanted and implanted)
Geometry:	+ 15° approach angle - 6° back rake - 6° side rake
Speed:	152.5 m/min. (500 fpm)
Depth of Cut:	2.54 mm
Feed:	0.125 mm/rev.

A filar-equipped low power microscope was used to measure flank wear.

Machining tests 20 minutes in duration (1200 seconds) were carried out in duplicate. Figures 4 and 5 show typical results obtained. A straight line is obtained when log flank wear (in μm) is plotted against log test time (in seconds).

Measured test data fitted to a line of the form

$$\log \text{(Flank wear)} = C_o + \log \text{(cutting time)}$$

is shown in Table V. Data from all eight tests carried out are shown in Table V together with the calculated coefficient of correlation.

Referring to Table V, it is noted that boron-implanted tools exhibit lower wear rate (line slope). Higher wear rate is obtained with carbon implantation. Nitrogen data is scattered.

Since only two tests were carried out for each implantation species, the data can only be taken to indicate a trend. The trend is that B and N_2 are *likely* to be beneficial. To obtain a more reliable evaluation, a statistically significant number of tests are necessary [some 8 to 10 for each species]. This is fairly expensive in terms of *both* test materials and man-power [Note: Each 20 minute test requires some 2 to 4 hours of testing.]

III.d. Cutting Tests (Force Measurement and Wear Studies) Heat Treated Samples

A diffusion treatment consisting of heating and holding at an elevated temperature (1000°C; 2 hours *at* temperature) was used to allow the implanted species to equilibriate excess species with the base material (TiC). A stainless steel muffle system was used.

The muffle box was first evacuated and back filled with commercial purity argon. Vacuum pump was then cut off and a positive pressure was generated within the muffle. The furnace was then turned on to bring the system to the desired temperature. It took approximately 90 minutes to bring the system to temperature. Test samples to be diffusion treated were placed in the muffle before evacuation.

Following the diffusion treatment, the muffle was allowed to cool slowly to 200°C (with continuous argon flow) and the samples were then taken out. Ion implanted and unimplanted inserts so treated were then tested for friction and wear characteristics.

Since only a limited number of implanted cutting inserts were available, all tests could not be carried out with fresh cutting edges. Data obtained whenever duplicate tests had to reuse a treated edge are indicated in tables and figures as "used".

Semi-orthogonal cutting force studies were carried out with a depth of cut of 2.54 mm and a feed rate of 0.250 mm/rev. Results are presented in Tables VI and Table VII ('used' inserts). No significant variation could be detected among implanted and unimplanted edges in tool-chip friction.

The change in power consumption when implanted and diffusion treated tools are used to machine AISI 1045 is shown in Table VIII. In all cases there is a decrease in power requirement for metal removal, even though the variation in operative friction is quite small.

Results of tool wear test studies are summarized in Figure 6 and Table IX. AISI 1045 Steel was machined at 152.5 m/min., with a depth of cut of 2.54 mm and a feed rate of 0.125 mm/rev. The conditions employed were the same as those used for previous tool wear studies with carbides.

Treated tools, boron and nitrogen implanted, do yield lower wear slopes indicative of beneficial effects due to ion implantation and diffusion treatment. An enhanced wear rate is observed in carbon-implanted tool. Data is based on "used" tools (B and N-Implanted) and should be treated with caution.

IV. Ion Implanted Taps and Tapping Tests

Previous work at Harwell with taps (working on plastics) implied that significant torque and wear reduction may be possible by ion implantation. Since the relative area in rubbing contact is large in tapping, this is not an unreasonable expectation. To see if this really is the case when metals are tapped, three 1/4"-20 taps were ion implanted at NRL and tested at Georgia Tech.

Mild steel (AISI 1018) flats, 1" x 1/2" were drilled at 600 rpm (#7 drill; standard drill for 1/4-20 taps) and tapped at a driving speed of 120 rpm. A commercial tap driver with an automatic reversing head was employed.

The first series of tests used "as implanted" taps with no lubrication. Tapping torque, following the first three holes increased rapidly and tap fractured following nine tapping operations. An unimplanted tap, washed in acetone, failed following three tapping operations. Since tap fracture was not the preferred failure criterion, all subsequent tests were carried out with an "effective pressure" tapping lubricant (mineral oil with sulfur-bearing additives).

The two remaining implanted taps were used for 50 and 100 tapping operations respectively. An unimplanted tap was also used to tap 100 threads (to obtain base data).

In course of the tapping tests a piezo-electric dynamometer was used to measure tapping torque and thrust. Variation in tapping torque was more sensitive to chemistry variation in the steel than any tribological property modification that may have accompanied ion implantation. SEM examination, See Figures 8 and 9, failed to reveal any noticeable variation in tap wear mode or characteristics.

The evaluation program undertaken is (based on results obtained) considered to be *inconclusive*. Taps, during their operating life, are prone to eventual failure by fracture. This follows accumulation of edge fracture at thread crests and the consequent increase in torque. This condition was not reached in the present tests.

Customarily, it is found that tap life is Weibull-distributed. Determination of the two parameters associated with Weibull distribution is essential before any judgement can be made of the usefulness of ion implantation to improve tap life. Some 20 to 40 taps are essential and experience, based on the work carried out here, suggests that each tap will have to be used to thread several hundred holes before any statistically significant result can be obtained.

V. Discussion of Test Results

In machining there is a finite length of contact (length BE in accompanying figure) between the tool and the chip. Over a part of this length (BD) the contact between the chip and the tool is plastic. The remainder of the contact is elastic. The applicable slip line field (determined with plasticity theory) consists of a region of plastic contact (BCD), a centered fan region (ACB) and an isolated slip line (OAB). It is schematically shown in Figure 10.

By ion implantation, it is expected that the frictional characteristics of the tool material can be altered to change the applicable boundary conditions (of the plasticity problem) which prevails during machining along BDE (the tool-chip contact length). A reduction in local friction coefficient leads to lowered frictional dissipation along BDE and *also* lower power requirements for machining through a lowering of chip shear strain during machining. The net result, apart from improving the energy efficiency during machining, is a lowering of the tool temperature which can result in a lowered wear severity encountered by the tool during machining.

Apart from changing the sliding friction coefficient, ion implantation is also known to improve the wear resistance. Improvement in wear resistance is ion-specific. A purpose of the present program is also to identify the appropriate ionic species and to document the relative improvement in wear resistance.

At the region of elastic contact between the tool and the chip, the ambient (atmosphere) interacts with the sliding wear process. Since the prevailing temperatures during cutting can be (and are) large along DE, oxidative wear (chemical or corrosive wear) is likely. Ion implantation is known to affect surface chemical and corrosion properties of implanted substrates. It is therefore expected that by ion implantation material loss rate from region DE can be lowered.

A similar reasoning holds for the flame wear region. Temperatures are however lower here and sliding contact (when it occurs) is less severe than in the crater region.

Examining now the data from the instrumented lathe tests it is noted that implantation has had little effect on tool-chip "friction". This is true for both the M-2 high speed steel inserts and for the carbide inserts. This result is at variance with previous tribological test results on the effect of ion implantation reported in the literature.

To resolve this anamoly, the implanted and unimplanted test samples were examined in the SEM. Figures 11a and 11b show the surface structure of the M-2 high speed steel inserts.

The surface of M-2 exhibits typical grinding grooves and is rough (Typical RMS value of the surface roughness of rough ground steel can go up to 40 micro-inches). This roughness is very much greater than the mean range of ion implantation. In implantation (under normal or oblique ion implantation conditions), the presence of significant roughness can lead to non-negligible sputtering.

Sputtering is known to be a momentum transfer-induced surface depletion (loss of surface material) process. Sputtering rate is a function of ion energy and substrate properties. A cosine sputtering law is known to operate.

The presence of substantial sample roughness, feather edges (on either side of grinding grooves) and large ion energies favors sputtering of the substrate. Clear cut evidence in support of test sample sputtering may be seen in Figures 11a and 11b. Feather edges of grinding grooves are apparently sputtered at a higher rate than the grooves. Within the grooves a fine scale structure is clearly observable at 6000X. Features produced are sub-micron in size and are therefore unlikely to be related to the grain size of the substrate.

The surface roughness of Singer's samples and bearings implanted by Hirvonen are not known. It is suspected that Singer used metallurgically-polished discs of AISI 52100 steel. Ball bearings are typically finished with an RMS surface finish of 0.5 to about 5 micro-inch. Previous work has thus involved implantation of finely finished surface.

It would thus appear that the lack of effect of ion implantation on the friction coefficient is at least partially attributable to unknown surface roughness and sputtering interactions. (Note: The edge of M-2 H.S.S. insert was implanted obliquely to embed Ti ions on the rake face, flank face and the trailing clearance face.) If this is a correct explanation, implantation of cutting tools of complex geometry is likely to pose preferential sputtering problems and should be undertaken with care. It would also appear that smooth implantation surfaces are desirable.

Sputtering and associated surface structure modification are possible in TiC-coated carbide tool inserts also. Figures 12 to 16 illustrate the SEM observations. Test samples implanted with normal incidence and oblique incidence are shown. As CVD-coated surfaces are also shown for comparison.

Significant surface structure modification and evidence in favor of preferential sputtering are seen in the SEM micrographs. Even 50 keV Boron induces substantial substrate surface structure modification.

The next point to be noted is that in machining, the forces generated by the sum of deformation and sliding work are measured as tool forces. Operative friction is calculated from the measured tool forces. Thus, any effect of ion implantation can be masked in the sum. This has always been and will continue to be (for the foreseeable future) a difficult problem. Whenever changes in friction are substantial (as when lead is incorporated in the work material), force measurements are useful to document unambiguous 'friction' reduction. Absence of any measurable reduction in the present series of tests does not imply that there has been any friction reduction (in the tribological sense). It is safe to conclude that there has been a small reduction. Reduction in specific power consumption for metal removal observed supports this view.

Tool wear tests on Titanium implanted H.S.S. inserts do indicate that wear rate reductions are possible by titanium ion implantation. Determination of the absolute magnitude of improvement requires a statistically significant number of tests.

Wear tests on carbide inserts (TiC-coated) suggest that meaningful improvements in tool life are possible when such tools are Boron and nitrogen implanted. Indications are that a diffusion treatment at 1000°C for two hours (or more) are desirable. Wear life improvement apparently accrues despite sputtering effects. As in the case of H.S.S. tools, additional tests (statistically significant in number) are necessary to establish the magnitude of improvement accompanying ion implantation.

Tests carried out suggest that carbon implantation of TiC-coated tools is not desirable.

Tapping tests carried out are not statistically significant. Work material effects are dominant and a fairly large test program is essential to evaluate the possible benefits of ion implantation.

Table I. Orthogonal cutting (two-dimensional cutting) test data. Comparison of implanted and unimplanted M-2 high speed steel tools. Width of cut = 2.54 mm and feed rate = 0.125 mm/rev. at indicated cutting speed. Triple replication.

Cutting Speed m/min	F_c Newtons			F_t Newtons			μ* Measured Friction Coefficient			ΔP** %		
Datum: Unimplanted tool												
20	851	847	859	409	405	368	0.62	0.61	0.56			
25	843	792	827	405	378	364	0.62	0.61	0.57			
30	804	764	788	378	369	355	0.61	0.62	0.58			
35	784	749	772	369	365	337	0.61	0.62	0.57			
40	756	733	756	365	360	328	0.59	0.63	0.56			
45	737	717	725	358	352	326	0.62	0.63	0.58			
50	721	693	693	356	338	309	0.63	0.62	0.58			
Implanted Tool												
20	717	804	789	334	352	355	0.60	0.57	0.59	-15.74	-5.07	- 8.14
25	693	768	749	332	343	337	0.61	0.58	0.58	-17.79	-3.03	- 9.43
30	662	744	725	320	334	327	0.62	0.58	0.58	-17.66	-2.61	- 7.99
35	646	725	693	318	325	319	0.63	0.58	0.59	-17.60	-3.20	-10.23
40	642	697	678	316	312	314	0.63	0.58	0.60	-15.07	-4.91	-10.31
45	640	678	662	307	307	309	0.60	0.59	0.60	-13.16	-5.43	- 8.68
50	634	662	638	303	303	305	0.61	0.59	0.61	-12.06	-4.47	- 7.93

*Significant effect on 'friction' is not noted.

**Data indicates (column 5) that specific power consumption for metal removal is lowered by ion implantation.

Table II. Effect of ion implantation on the tool-chip 'friction' during machining as a function of cutting speed. A medium carbon steel was machined with tool inserts. Carboloy 515/516 inserts machining AISI 1045. Depth of cut of 2.54 mm and feed rate of 0.125 mm/rev.

	Calculated friction coefficient in semi-orthogonal cutting			
Cutting Speed meters/min	Unimplanted	Carbon implanted	Boron implanted	Nitrogen implanted
100	0.660	0.725	0.741	0.734
130	0.709	0.704	0.712	0.728
160	0.704	0.695	0.699	0.713
190	0.700	0.686	0.681	0.693
220	0:698	0.664	0.625	0.685

Table III. Effect of ion implantation on the specific power consumption* in machining. Percent change is tabulated with the unimplanted tool as the datum. Carboloy 515/516 inserts machining AISI 1045 with a depth of cut of 2.54 mm and a feed of 0.125 mm/rev.

Cutting speed m/min.	Implanted Species Carbon	Boron	Nitrogen
100	- 11.4	+ 2.3	+ 5.7
130	- 1.9	+ 4.6	+ 1.9
160	- 2.0	- 4.6	- 1.0
190	- 6.2	- 0.1	- 4.5
220	- 7.7	0	- 4.7

*Specific power consumption = Power dissipated per unit volume of metal removed. Includes the deformation and frictional component.

Table IV. Measured force components in semi-orthogonal cutting while machining AISI 1045 with carbide inserts. Depth of cut = 2.54 mm. Feed = 0.125 mm/rev.

	Cutting Speed m/min.	Force Components (Newtons) F_c	F_t	F_r
A.	Unimplanted Insert			
	100	954	734	291
	130	843	698	258
	160	758	649	237
	190	780	640	232
	220	777	636	228
B.	Carbon Implanted			
	100	847	712	288
	130	827	680	254
	160	772	631	241
	190	732	587	224
	220	717	556	215
C.	Boron Implanted			
	100	977	845	310
	130	882	725	306
	160	824	667	275
	190	780	618	245
	220	776	614	232
D.	Nitrogen Implanted			
	100	1008	866	310
	130	858	732	267
	160	780	650	241
	190	745	605	224
	220	740	596	216

Table V. Tool wear test data

AISI 1045 Steel machined with implanted carbide inserts (Carboloy 515/516) at 152.5 m/min. Depth of cut = 2.54 mm; feed = 0.125 mm/rev.

$$\log (FW)^* = Co + \log (CT)^{**}$$

$$Y = mx + C_o$$

Implant Species	Regression Line		Correlation Coefficient
	m	C_o	
None - 1	0.4153	0.8728	0.9931
None - 2	0.4683	0.6807	0.9796
Carbon - 1	0.4671	0.6899	0.9872
Carbon - 2	0.4573	0.7160	0.9849
Nitrogen - 1	0.3557	0.9921	0.992
Nitrogen - 2	0.5108	0.5605	0.9947
Boron - 1	0.3829	0.8626	0.9595
Boron - 2	0.3985	0.9098	0.9963

*FW = Flank wear (μm)

CT = Cutting Time (seconds)

Table VI. Semi-orthogonal Cutting Tests

AISI 1045 machined at indicated cutting speed.
Depth of cut = 2.54 mm. Feed = 0.250 mm/rev.*

Cutting Speed m/min.	Measured forces (Newtons) F_c	F_t	F_r	Friction** coefficient μ
A. Unimplanted				
100	1955	1361	500	0.58
130	1890	1237	475	0.53
160	1874	1165	462	0.52
190	1826	1112	449	0.51
220	1809	1076	445	0.50
B. Carbon-Implanted				
100	1753	1183	470	0.57
130	1745	1130	462	0.55
160	1741	1068	449	0.52
190	1737	1041	445	0.51
220	1729	1032	440	0.53
C. Nitrogen-Implanted				
100	1820	1290	517	0.60
130	1761	1174	487	0.56
160	1721	1103	474	0.55
190	1688	1050	462	0.53
220	1672	1032	457	0.52
D. Boron-Implanted				
100	1818	1237	513	0.58
130	1761	1165	500	0.56
160	1745	1112	496	0.54
190	1733	1094	496	0.54
220	1729	1076	493	0.53

Note: *Feed rate *twice* that for untreated inserts

**Calculated values

Table VII. Semi-orthogonal cutting tests

AISI 1045 machined at indicated cutting speed. Depth of cut = 2.54 mm. Feed = 0.25 mm/rev.

Cutting Speed	Measured Forces (Newtons) F_c	F_t	F_r
A. Carbon-Implanted (wear = 46 μm)			
100	2058	1427	500
130	1999	1290	496
160	1979	1221	466
190	1786	1183	460
220	1771	1125	440
B. Nitrogen-Implanted (wear = 37.5 μm)			
100	1862	1304	510
130	1803	1232	493
160	1783	1175	481
190	1774	1117	479
220	1761	1065	466
C. Boron-Implanted (wear = 38.7 μm)			
100	1901	1281	571
130	1822	1220	551
160	1783	1195	520
190	1750	1183	504
220	1710	1108	496

Table VIII. Change in power consumption for metal removal. Unimplanted tool is reference (based on data of Table VI).

Cutting Speed m/min.	Change in Power consumed $\Delta P\%$		
	C-Implant	N_2-Implant	B-Implant
100	-10.32	-6.92	-7.02
130	- 7.69	-6.83	-6.83
160	- 7.11	-8.18	-6.90
190	- 4.87	-7.55	-5.09
220	- 4.46	-7.61	-4.46

Table IX. Tool wear test data. Implanted tools "diffusion annealed" at 1000°C for two hours after implantation. AISI 1045 steel machined at 152.5 m/min. Depth of cut = 2.54 mm. Feed 0.125 mm/rev.

Measured data fitted to a curve of the form

$$\log (FW^*) = Co + \log (CT)^{**}$$

$$Y = mx + Co$$

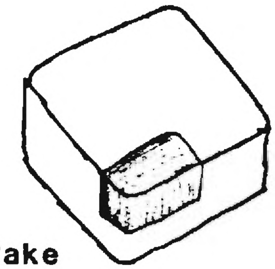
Implant Species	Regression Line m	Regression Line Co	Coefficient of Correlation
None[1]	0.2859	0.9887	0.988
Carbon[1]	0.341	0.859	0.987
Boron[1]	0.338	0.846	0.975
Boron[2]	0.083	1.738	0.950
Nitrogen[2]	0.107	1.708	0.991

*FW = Flank wear (μm)

**CT = Cutting time (seconds)

[1] Fresh edge used

[2] "used" edge. Note the larger intercept. "used" tools have an initial wear land of about 40 to 50 μm.

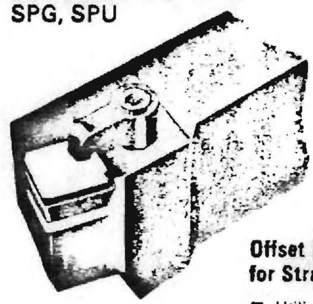


Schematic illustration of ion implanted, 1/2" x 1/2" high speed steel tool inserts. M-2 High speed steel inserts were used. Crater face and flank faces were implanted with 150 keV titanium ions. Implanted region is shaded.

Posive Rake Toolholder

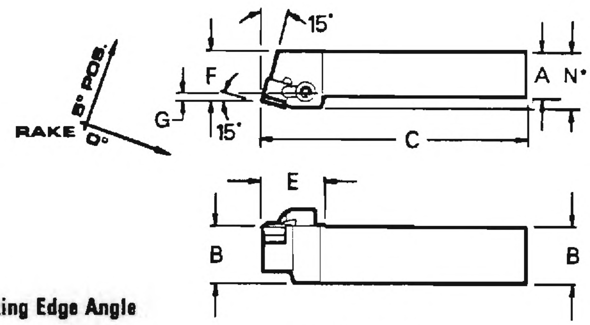
STYLE B Square

SPG, SPU



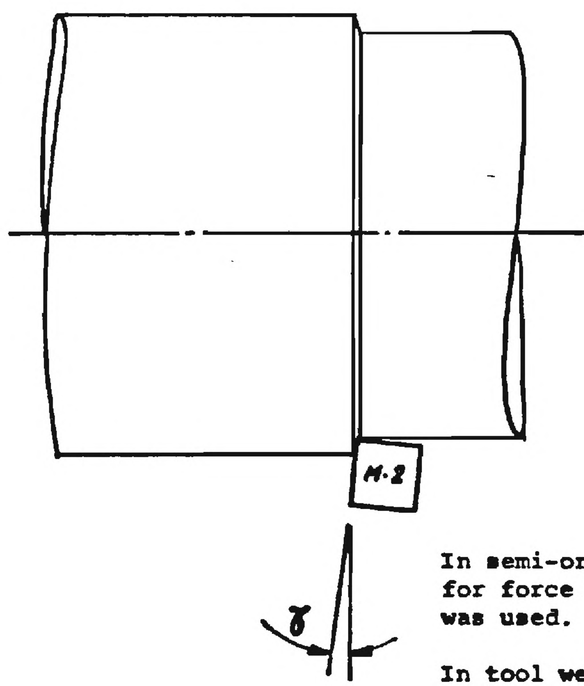
Offset Shank 15° Side Cutting Edge Angle for Straight Turning

- ☐ Utilizes Square Insert for Strength
- ☐ 15° S.C.E.A. Protects Insert Nose Radius and Thins Chip
- ☐ Free Cutting Conventional Positive Rake Geometry
- ☐ Fully Qualifiable (T.S.C. on Width Control; O.N.R. on Length Control) for N/C Equipment



RIGHT HAND SHOWN

* FOR "N" DIMENSION ADD .250 TO "A".



In semi-orthogonal cutting tests for force measurements, $\gamma = 5^{\circ}$ was used.

In tool wear tests $\gamma = 15^{\circ}$ was used.

Figure 1. Tool insert, tool holder and cutting geometry.

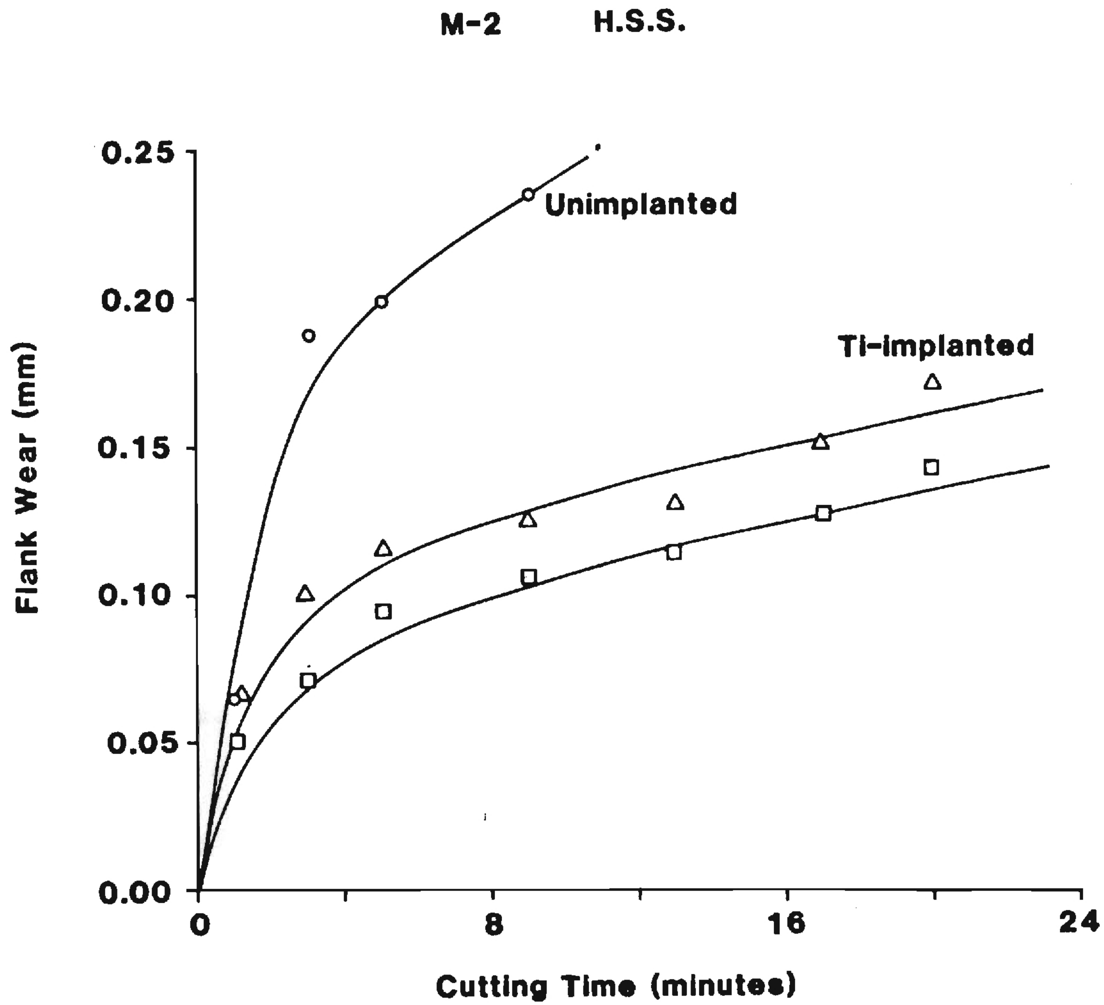


Figure 2. Tool wear test data. M-2 H.S.S. inserts machining a 1045 steel bar at 33.5 m/min. Depth of cut = 2.54 mm. Feed = 0.125 mm/Rev.

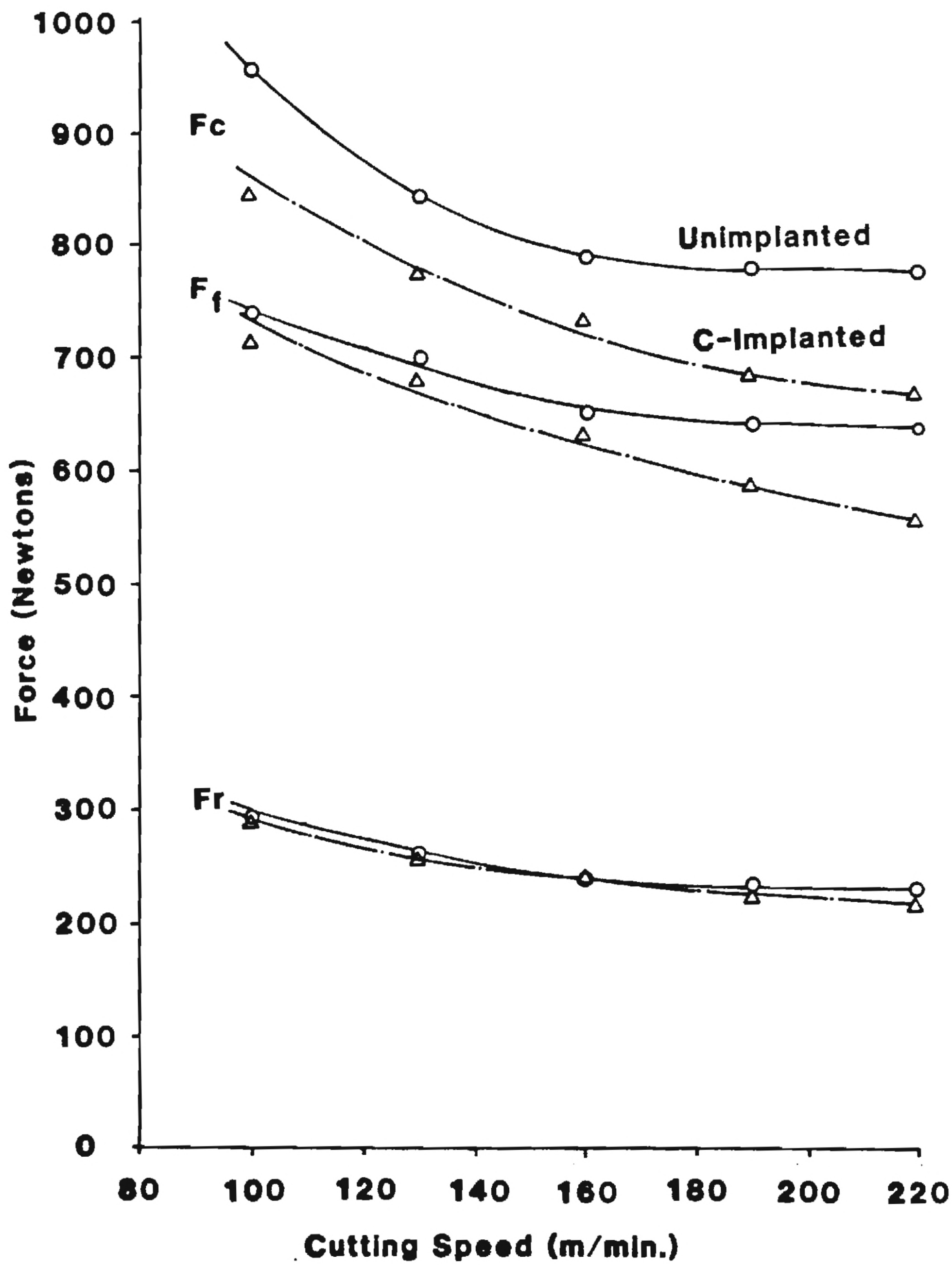


Figure 3. Measured force components when AISI 1045 is machined with unimplanted and carbon-implanted, TiC-coated tool inserts (F_c = power component; F_t = feed component; F_r = radial component). Depth of cut = 2.54 min; Feed = 0.125 mm/Rev.

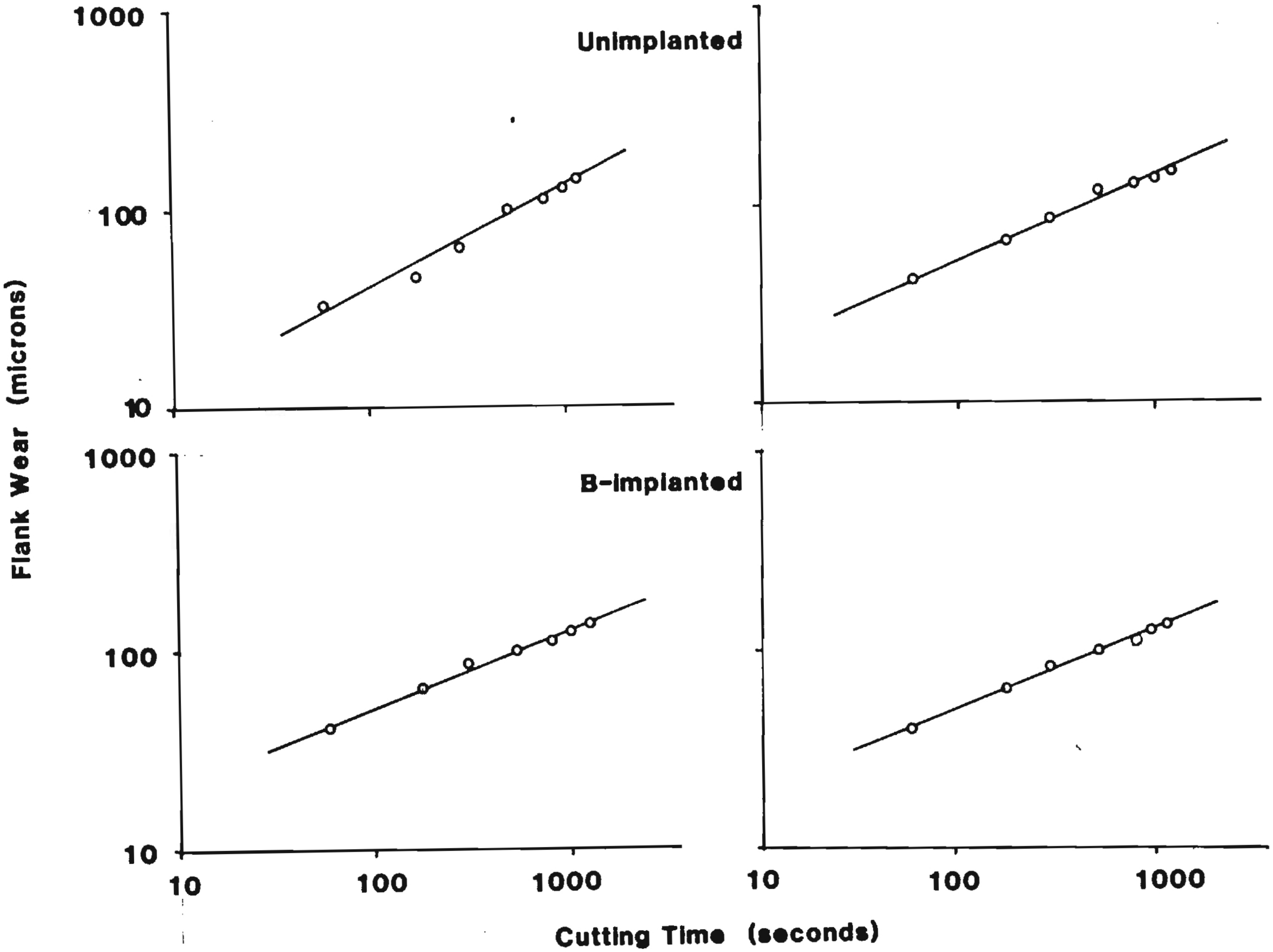


Figure 4. Tool wear test results. Unimplanted and Boron implanted tools were used to machine AISI 1045 at 152.5 m/min. Tests were duplicated.

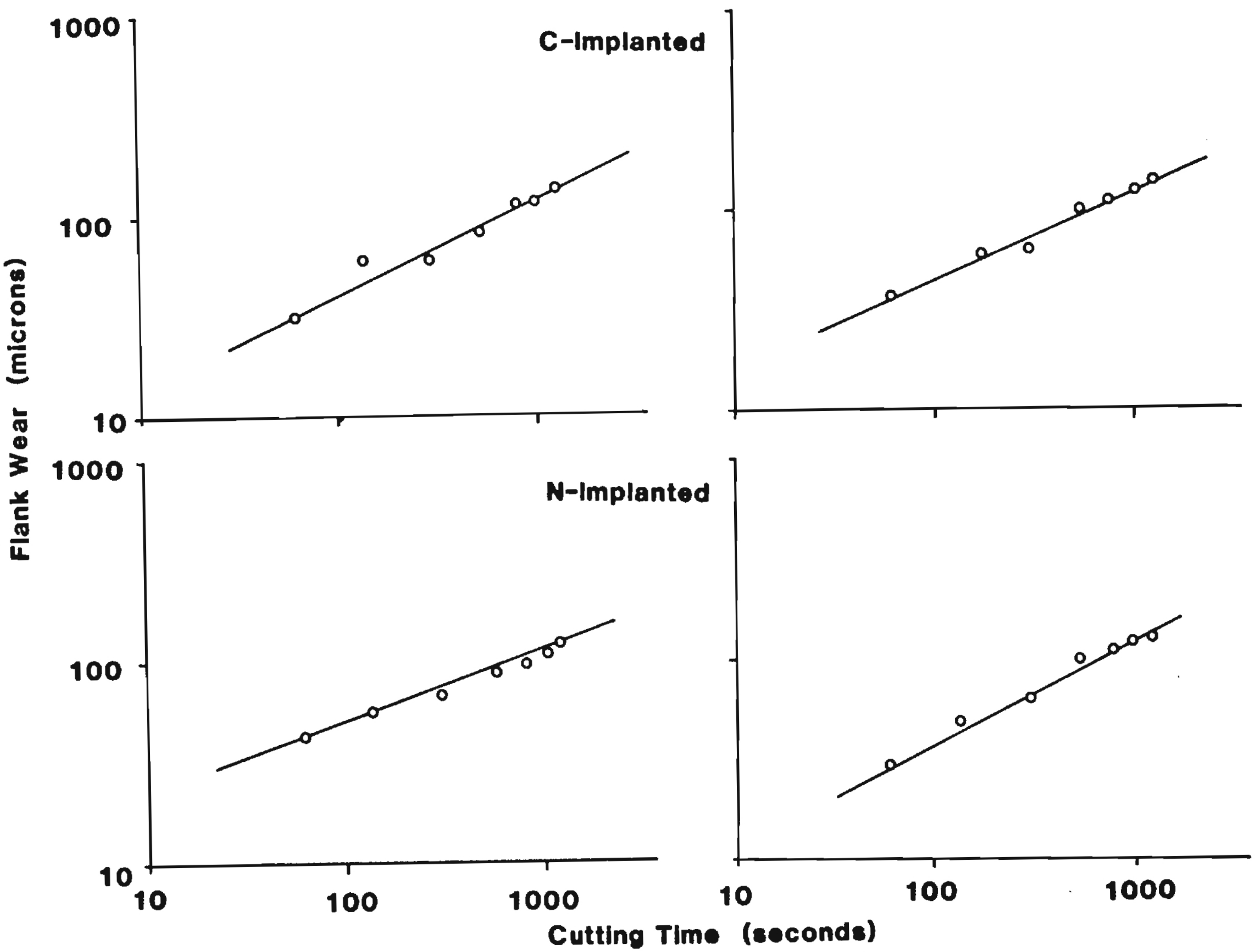


Figure 5. Tool wear test results. Carbon and nitrogen implanted tools were used to machine AISI 1045 at 152.5 m/min. Tests were duplicated.

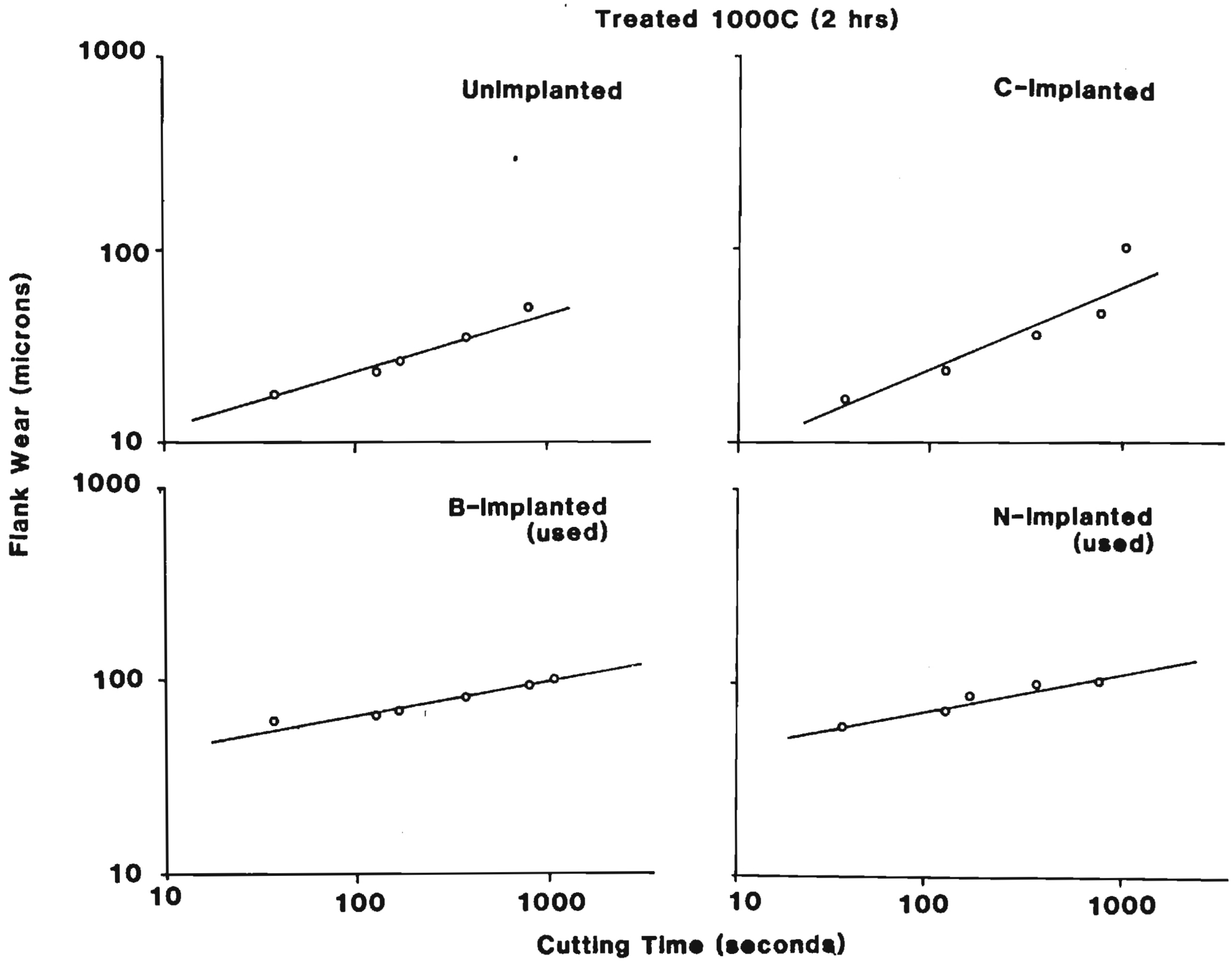


Figure 6. Tool wear test results. Tools treated at 1000°C for two hours were used to machine AISI 1045 steel at 152.5 m/min.

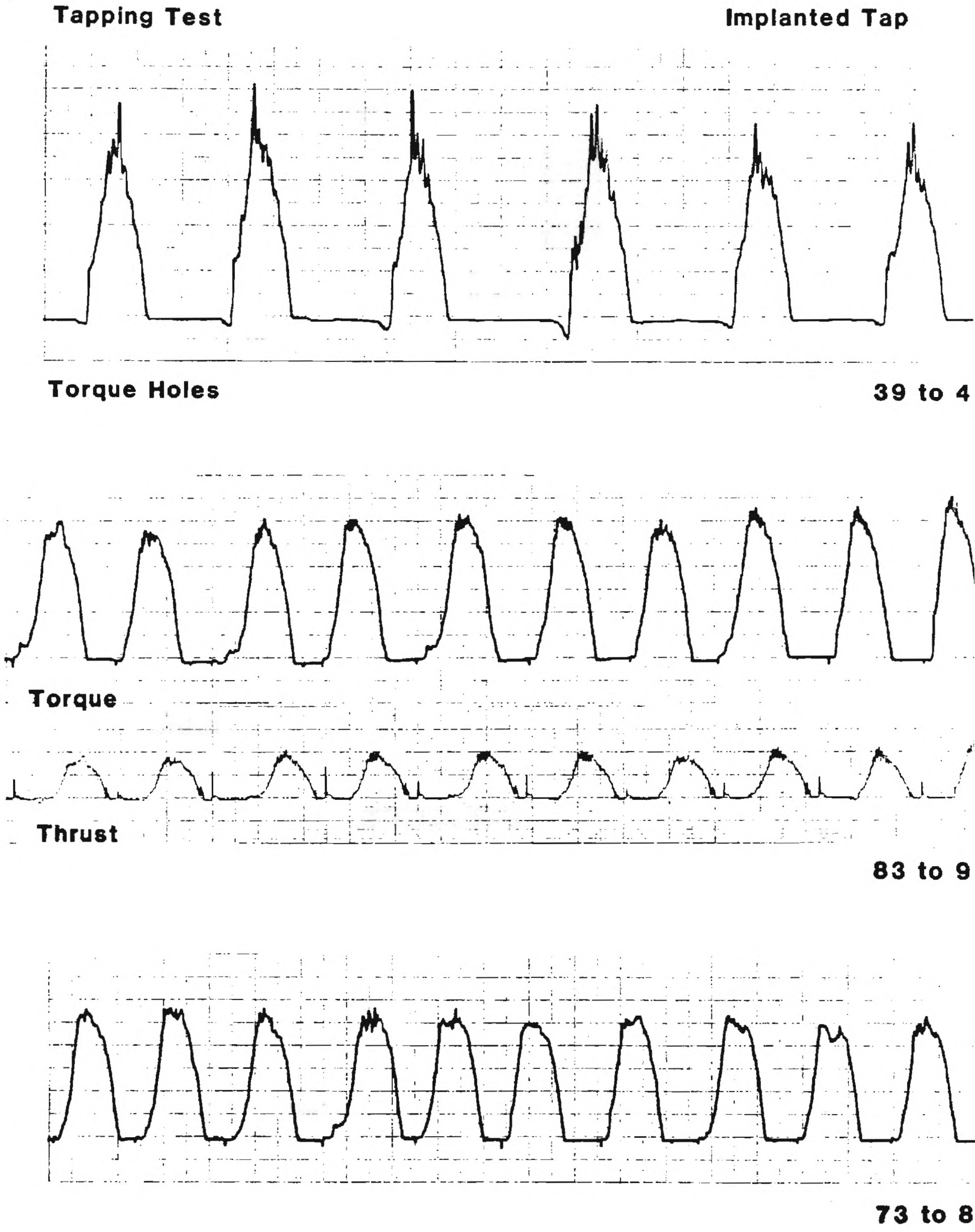
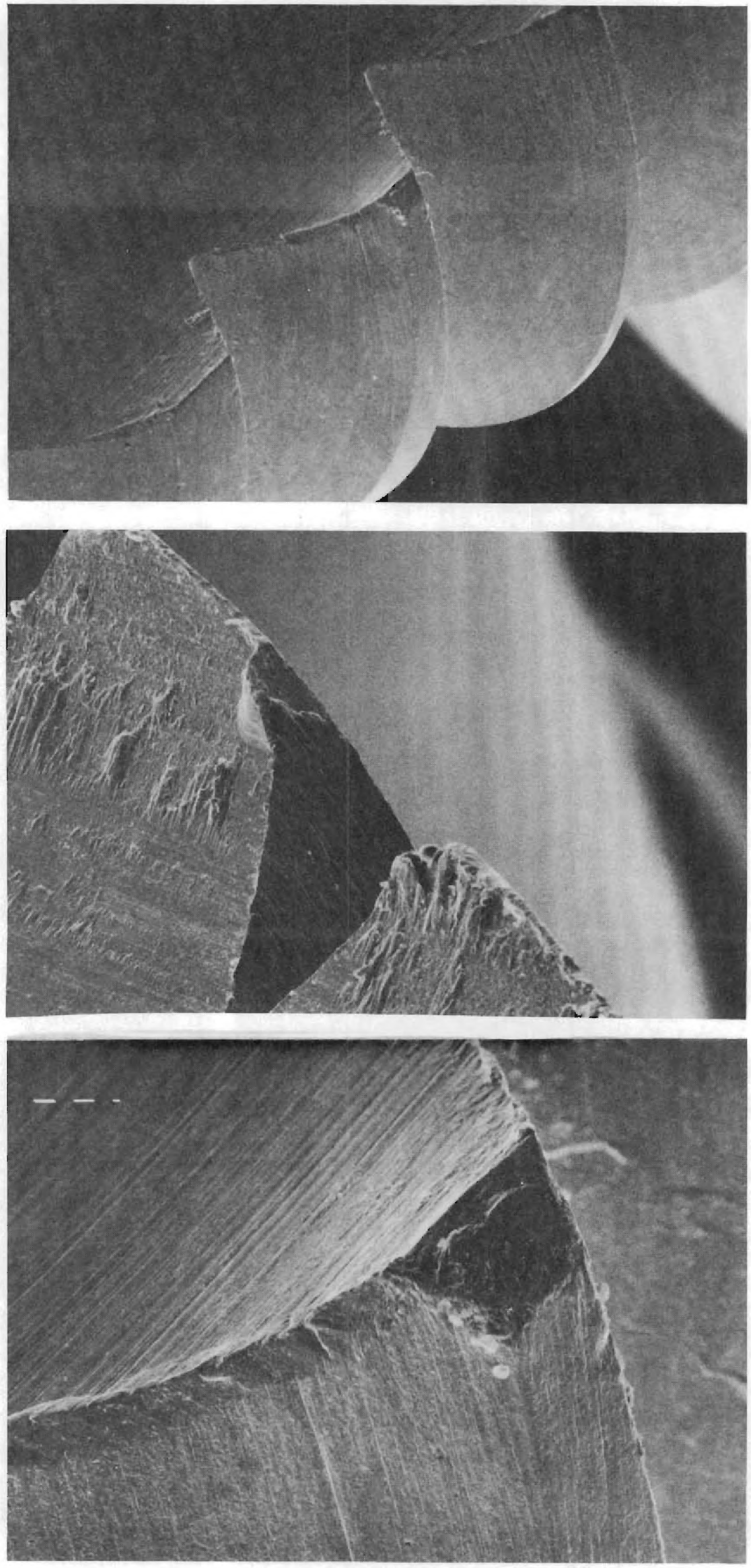


Figure 7. Tapping torque and thrust when implanted taps are used. Note that torque variation with location along test bar dominates.

Unimplanted H.S.S. Tap (used)



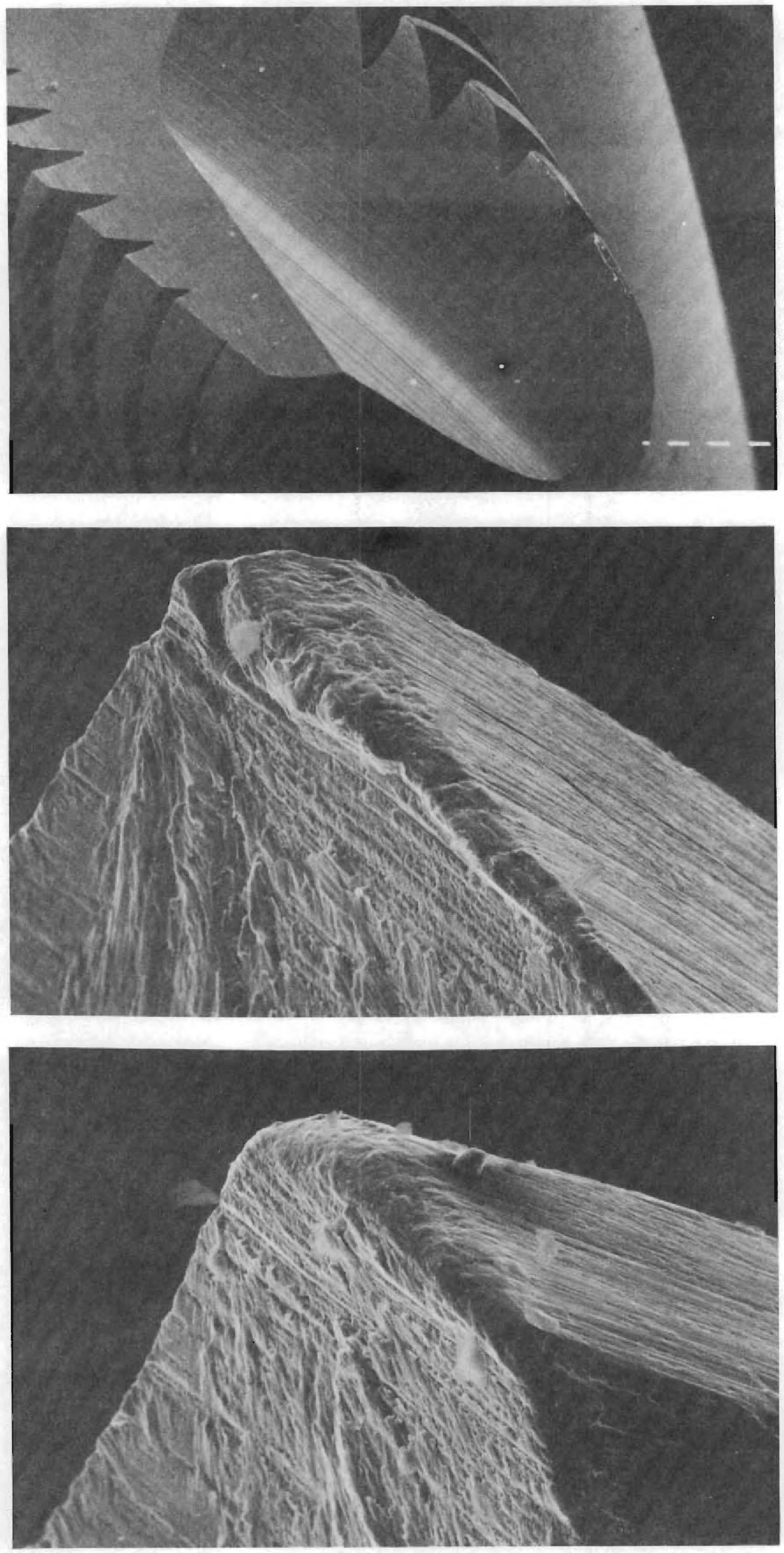
30X

110X

97X

Figure 8. SEM micrographs of unimplanted tap after 50 uses. Third and fourth crest are illustrated at higher magnification.

Implanted H.S.S. Tap

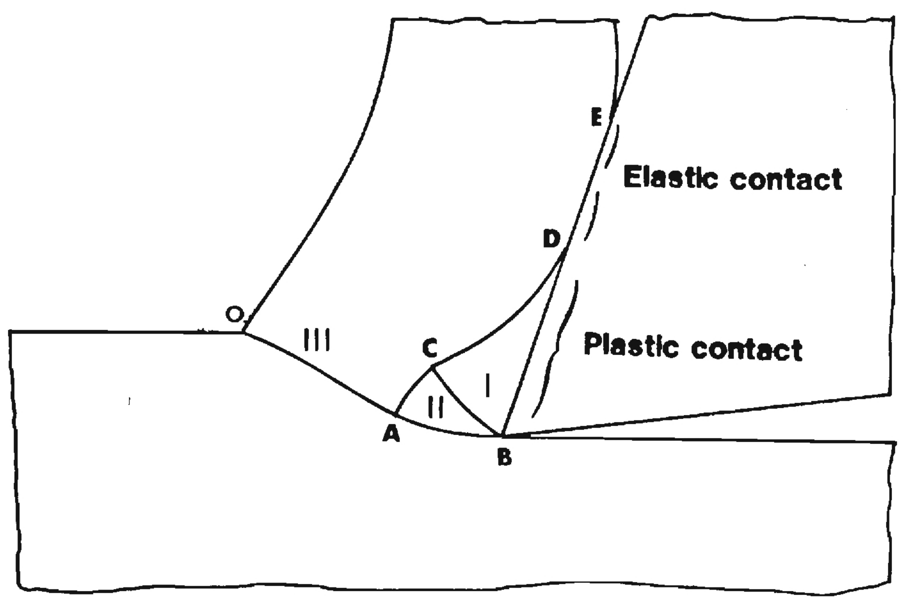


90X

3rd Edge 290X

4th Edge 290X

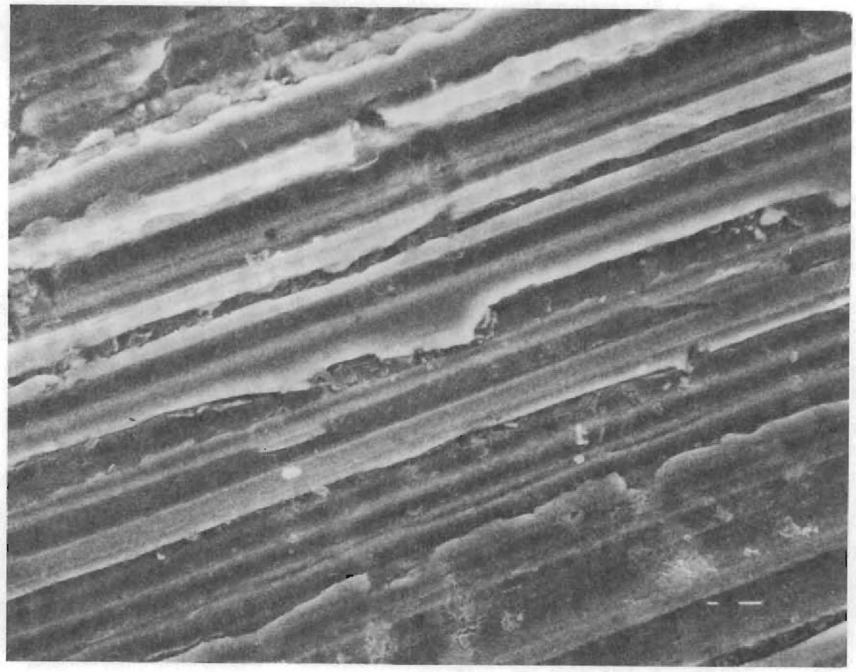
Figure 9. SEM micrograph of implanted tap after 50 uses.



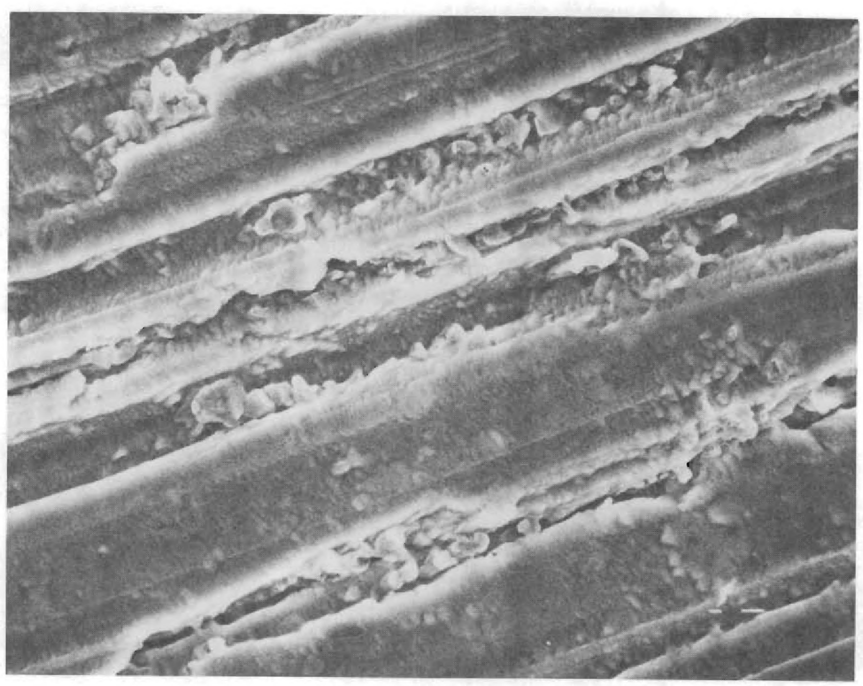
Slip Line Field for Machining

Figure 10. Slip line field for machining.

M-2 H.S.S.



Unimplanted Region 1500X

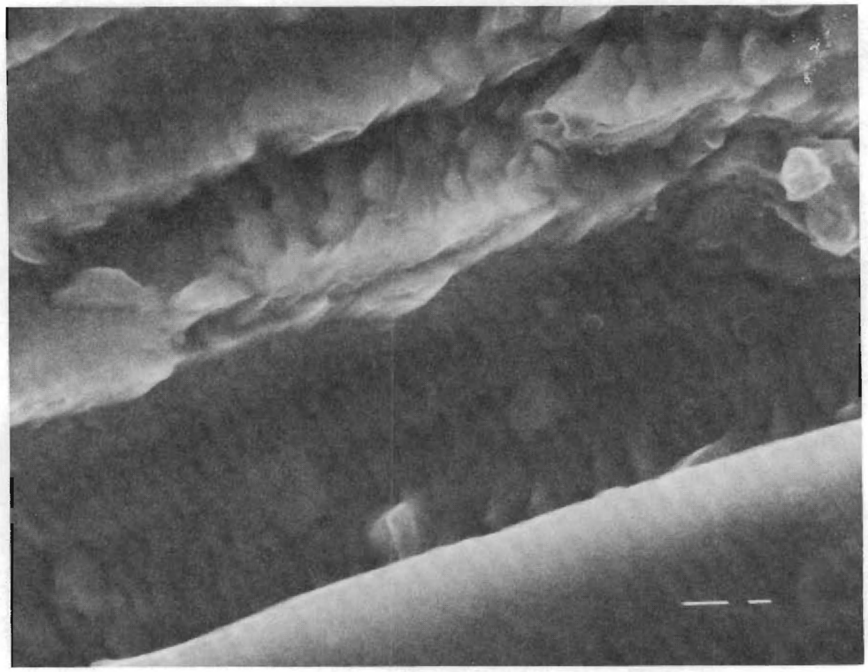


Implanted Region 1500X

Figure 11.a. SEM micrograph of unimplanted and implanted M-2 H.S.S. insert.

Implanted M-2 H.S.S.

Fine Structure at 6000X



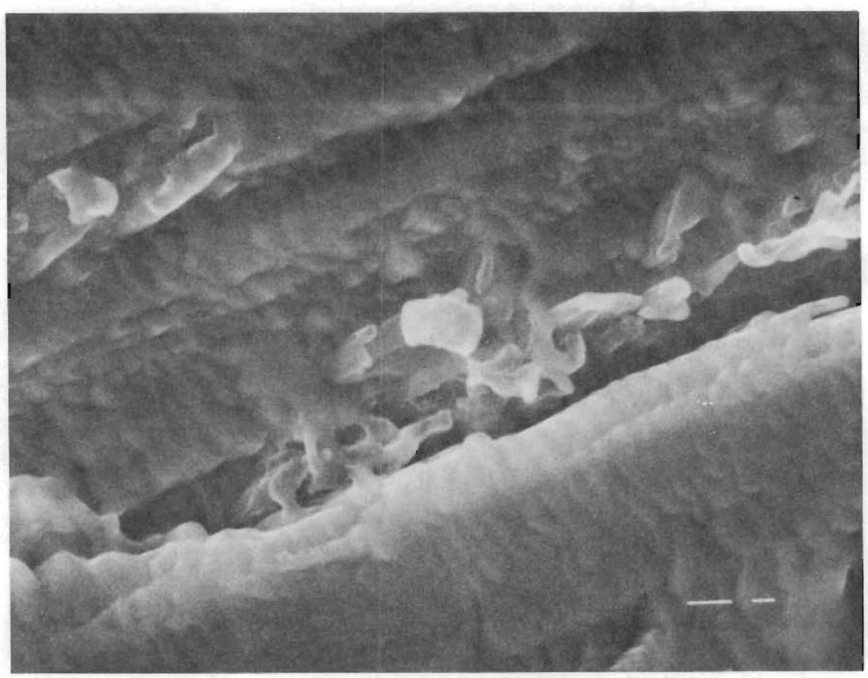
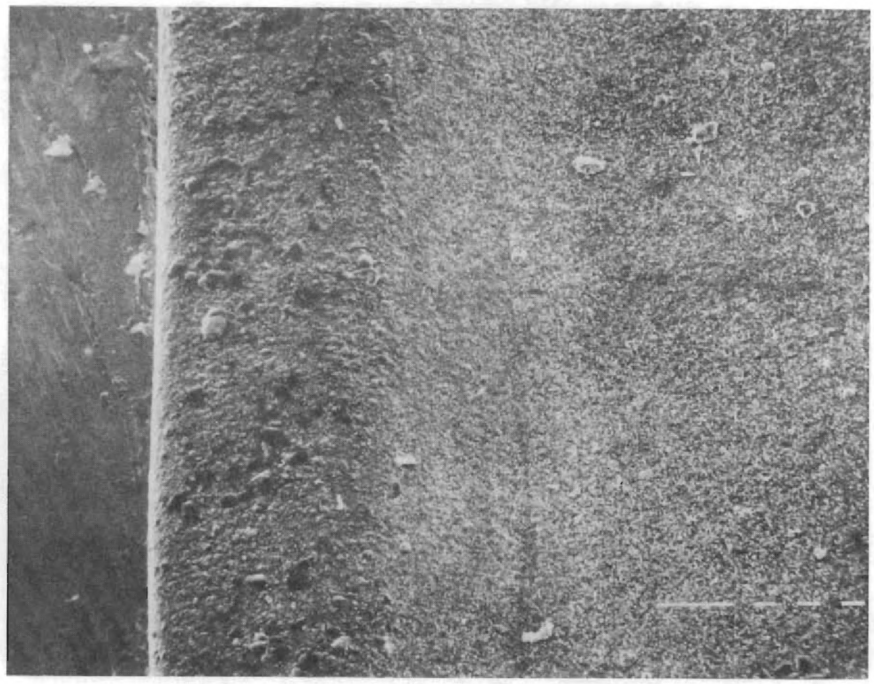


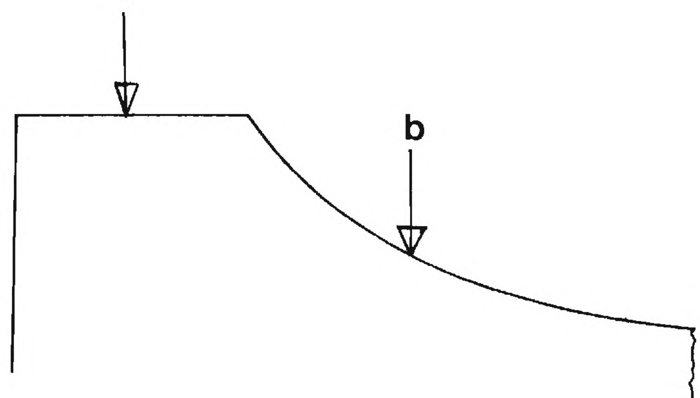
Figure 11.b. Fine structure generated by titanium (150 Kev) implantation of hardened M-2 H.S.S.

B-implanted TiC-coated Insert

Normal Incidence 50 Kev



Surface at 100X

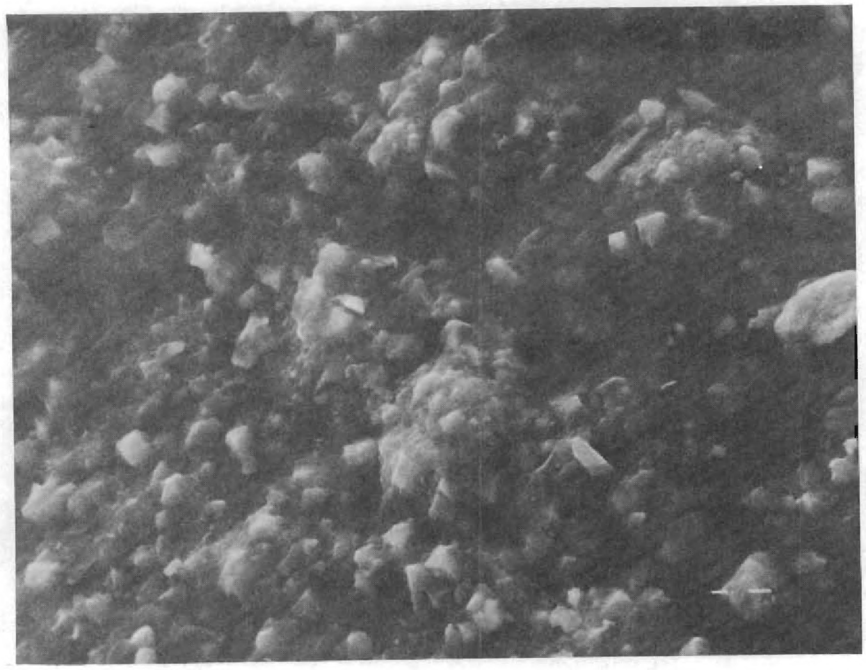


Section of Tool Profile

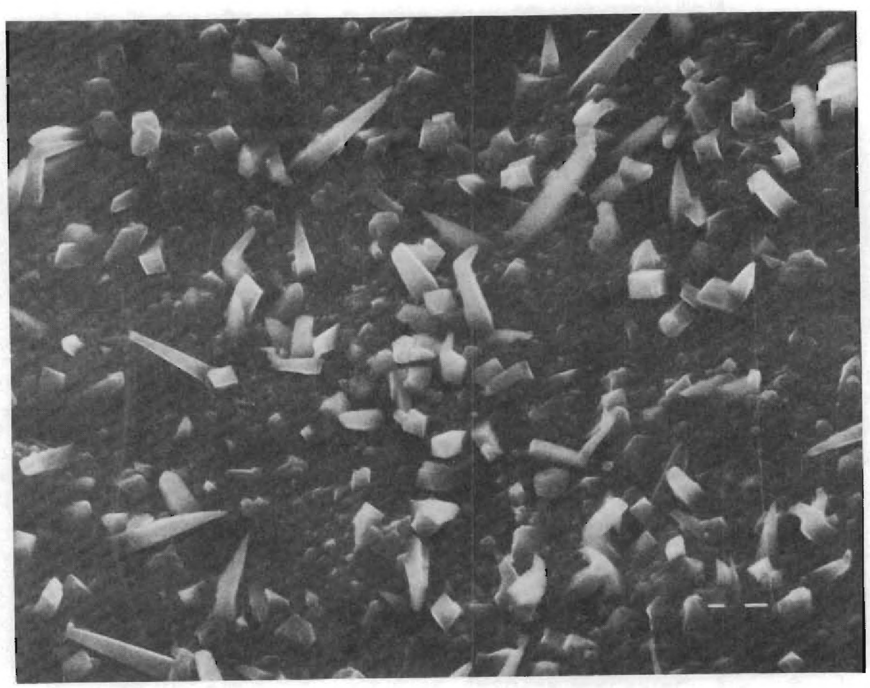
Figure 12. View of boron-implanted, TiC coated tool.

B-implanted TiC-coated Insert

50 Kev



Normal Incidence Region 2300X

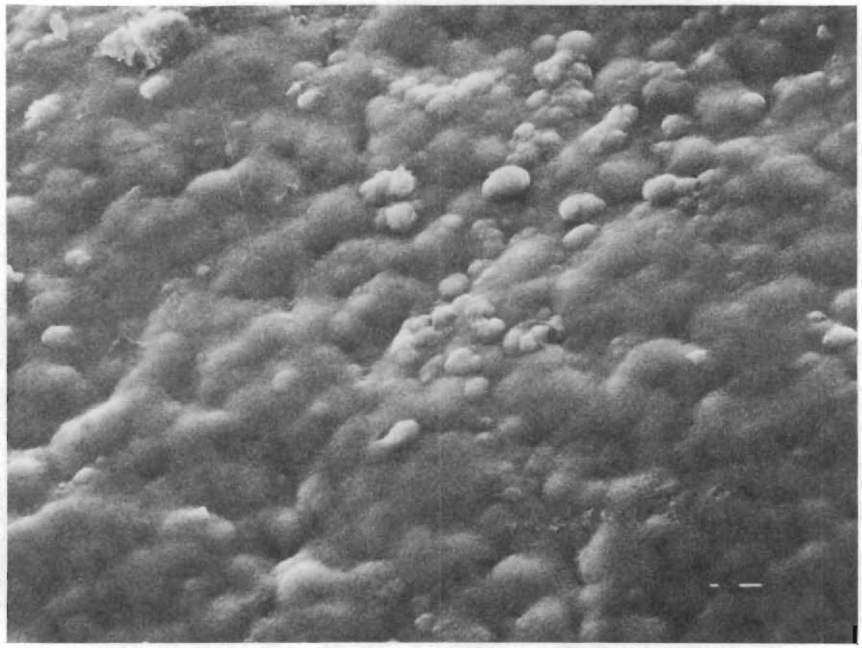


Oblique Incidence Region 2300X

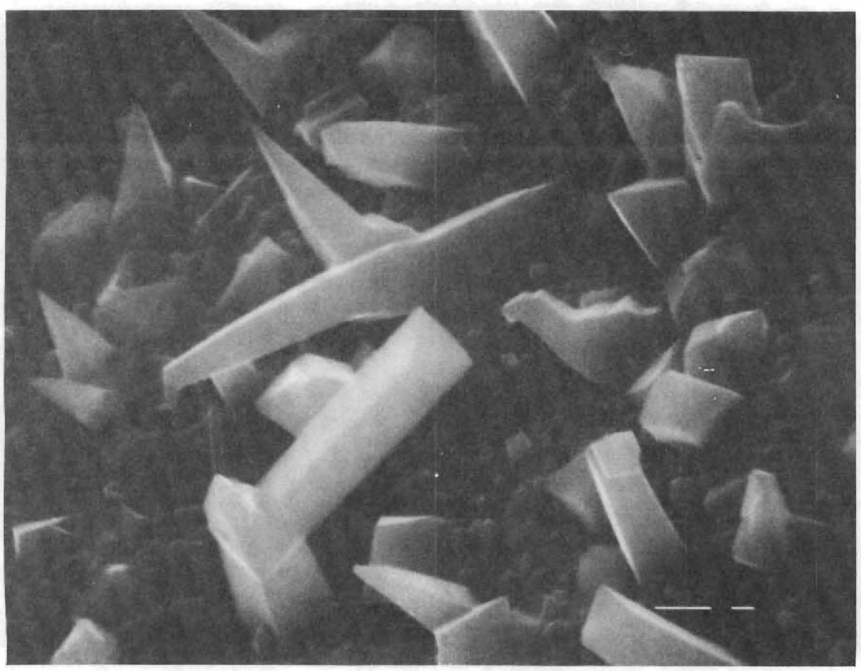
Figure 13. TiC-coated tool. Normal incidence of B modifies surface structure slightly. Location a of Figure 12. Oblique incidence sputters strongly. Location b of Figure 12.

Effect of B-implantation

50 Kev

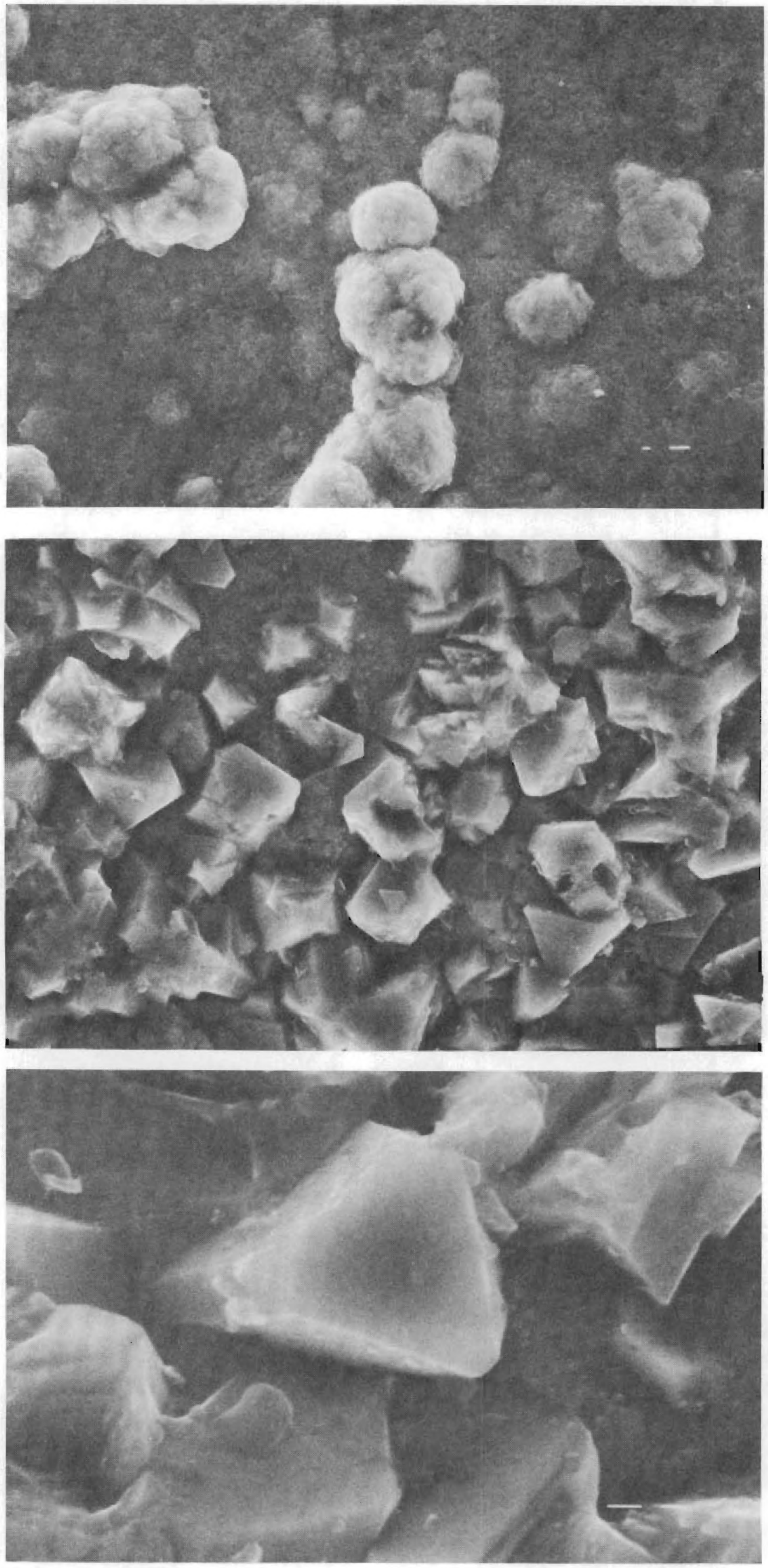


As CVD-coated Tool Surface 1200X



Oblique Implantation 7500X

Figure 14. TiC-coated tool. As coated surface and surface modification by Boron implantation. Location (b) of Figure 12.



As coated:

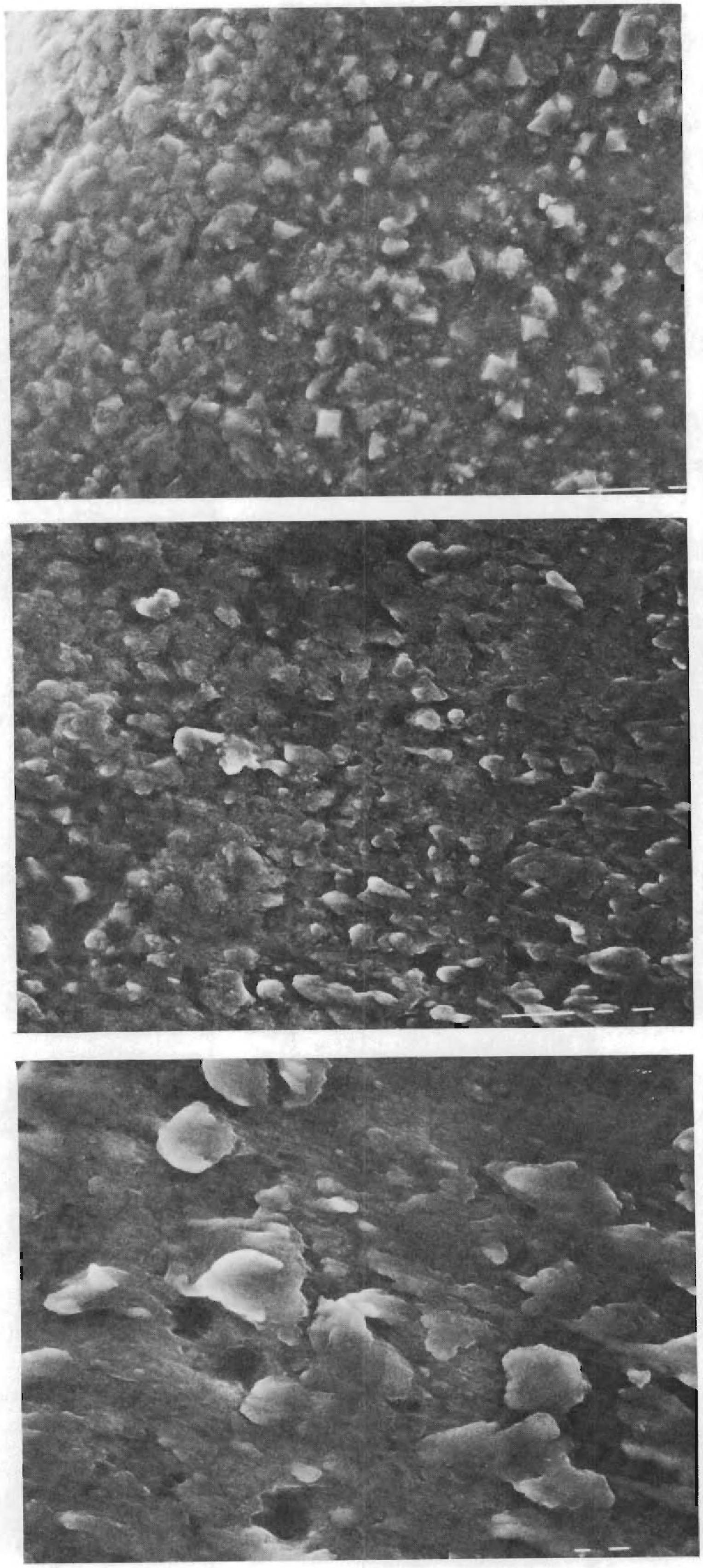
B-Implanted 1400X

N-Implanted 5000X

Oblique Implanted Note: Substrate is different.

Figure 15. TiC-coated tool ion implanted tool. Note the sputtering effects.

TiC-coated (515). C-implanted.



Used edge 1020X

As Implated 1020X

Used edge 2400X

Figure 16. TiC-coated carbide tool C-implanted and used. [diffusion treated].